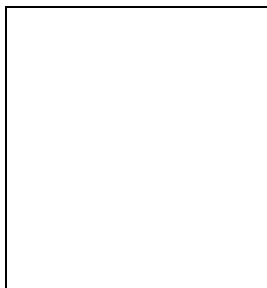


W-PAIR PRODUCTION AT LEP

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We review here the measurements of W-pair production and W decay rates performed by the four LEP experiments at \sqrt{s} from 161 to 209 GeV, and their relevance in support of the standard electroweak model.

1 Introduction

From July 1996 to November 2000 the LEP collider at CERN has delivered e^+e^- collisions above the kinematic threshold of the W-pair production, at \sqrt{s} ranging from 161 to 209 GeV, for a total integrated luminosity of about 700 pb^{-1} per experiment. The total collected data samples yielded about 10000 W-pair events per experiment, and allowed the first precision measurements of partial and total WW cross sections at different \sqrt{s} energy points, as well as the first direct determinations of all W decay Branching Ratios, to be achieved.

1.1 W-pair production in the Standard Model

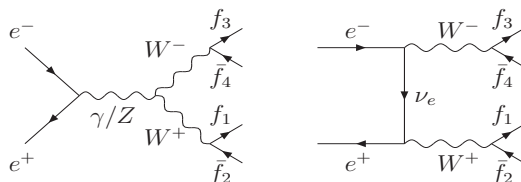


Figure 1: W-pair production in e^+e^- collisions: Standard Model CC03 diagrams.

In the electroweak model the $e^+e^- \rightarrow W^+W^-$ reaction is described, at lowest level, by the three diagrams shown in Figure 1 and referred to as CC03 diagrams. Among these production

diagrams the t -channel ν_e -exchange has well established $We\nu_e$ coupling vertices, while the two diagrams with the s -channel γ and Z boson exchanges involve $WW\gamma$ and WWZ triple gauge couplings that were not determined before the start of the LEP data taking above the W -pair threshold. The rôle of the triple gauge couplings is crucial. In fact for the W -pair production the t -channel contribution alone grows rapidly with energy ($\sigma_\nu \sim s$), violating unitarity, while the addition of the interference effects of the γ and Z s -channel cancels this divergent behaviour and leads to a cross-section which decreases at high energy ($\sigma \sim \ln s/s$). The CC03 W -pair production is therefore crucially determined by cancellations arising from the coupling coefficients dictated by the electroweak model's $SU(2)\otimes U(1)$ gauge invariance¹.

2 Event selections

The event topologies and selection criteria used to select W -pair events^{2,3,4,5} are mainly differentiated according to the possible leptonic ($W \rightarrow \ell\nu$) or hadronic ($W \rightarrow qq'$) decay of each W boson. The resulting four decay fermions are energetic ($E_f \sim \sqrt{s}/4 \sim 50$ GeV) and mutually isolated.

In the case of fully leptonic decays both W 's decay in a lepton-neutrino pair. This decay generates a low particle multiplicity and a large missing momentum transverse to the beam line. Further the two selected primary leptons will be energetic and have a large acoplanarity in the plane transverse to the beam line. The achieved signal selection efficiency is 60-80% with a purity of 90-80%. Residual backgrounds come from $e^+e^- \rightarrow \tau^+\tau^-$ and $\gamma\gamma \rightarrow \ell^+\ell^-$ processes.

In the semi-leptonic channel ($WW \rightarrow \ell\nu qq'$), the primary lepton is energetic and isolated from the two jets of the hadronic system. The primary neutrino will produce a large missing momentum vector, also isolated in space. In this channel signal efficiencies are in the 60-90% range with corresponding purities of 95-85%. Main backgrounds originate from $q\bar{q}$ events with energetic leptons from heavy quark decays, and other four fermion processes as $e^+e^- \rightarrow ZZ^*$, Zee .

Fully hadronic W -pair decays result in four jet events without missing energy, characterised by a very large particle multiplicity with a spherical momentum distribution. Many observables based on the global event topology and on the jets kinematics are used to select these events, resulting in signal efficiencies of 60-80% and purities of 85-75%. The largely dominant background is generated from non-radiative $q\bar{q}$ events with hard QCD gluon emissions.

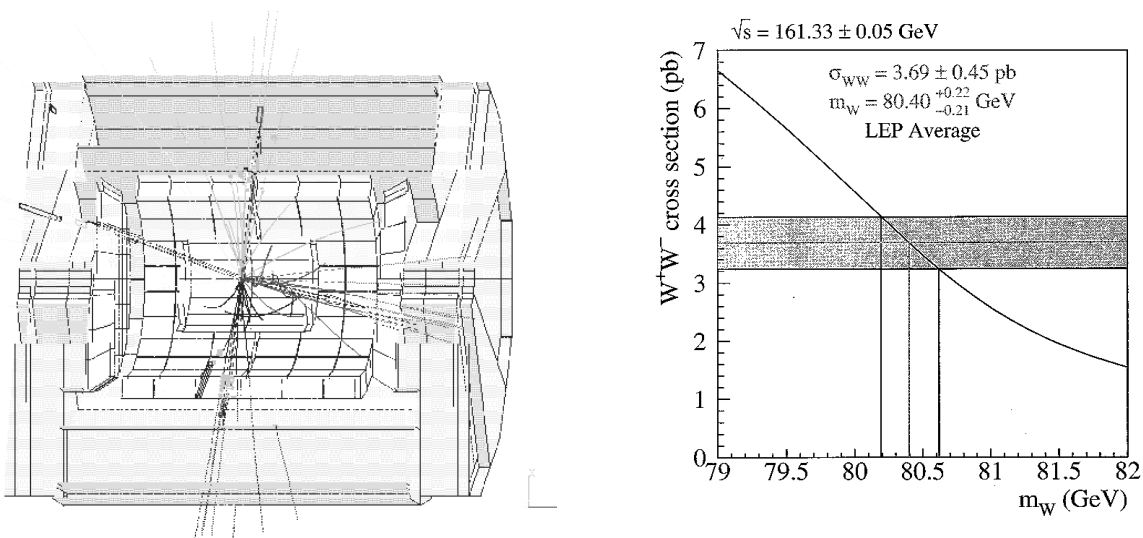


Figure 2: (left): The first W -pair event seen at LEP: a $q\bar{q}q\bar{q}$ decay in DELPHI at $\sqrt{s}=161$ GeV. (right): W -pair cross section at $\sqrt{s}=161$ GeV as a function of the W mass. The shaded band indicates the LEP determination.

3 Extraction of W-pair cross sections

Partial and total cross sections are determined through maximum likelihood fits to the number of selected events in each decay channel, assuming Poisson distributions for the numbers of observed events. The W-pair cross section yields⁶ obtained with the full LEP data sample at $\sqrt{s}=161$ -207 GeV are shown in figure 3 and are compared with calculations of the Standard Model CC03 production. The agreement of experimental results with such theoretical expectations is the first clear evidence of the existence of both the $WW\gamma$ and WWZ couplings with the expected electroweak $SU(2)\otimes U(1)$ coefficients.

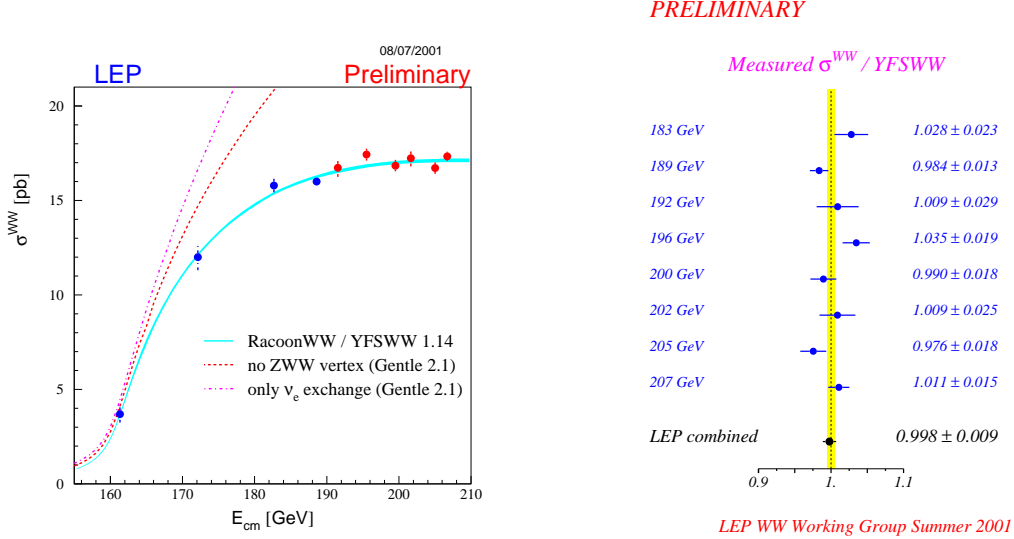


Figure 3: (left): Measurements of the total W-pair production cross section and comparisons with Standard Model predictions as a function of \sqrt{s} . The data points clearly proof the existence of both the $WW\gamma$ and WWZ couplings with the expected electroweak $SU(2)\otimes U(1)$ amplitudes. (right): Ratio of measured W-pair cross sections to Standard Model calculations with $O(\alpha)$ radiative corrections. The overall precision on σ^{WW} is around 1%.

It should be remarked that the theoretical calculations include first order electroweak radiative corrections in the so called Double Pole Approximation⁸ (DPA), and that the data results disfavour calculations without $O(\alpha)$ corrections by almost 2.5 sigmas. This result tells us that the overall LEP precision ($\sim 1\%$) obtained on σ^{WW} allowed us to test the Standard Model CC03 production at the one loop level.

3.1 W mass from the threshold production rate

As shown in figure 2, the W-pair cross-section at the production kinematic threshold is very sensitive to the W mass value, so that the LEP measurement of σ^{WW} at $\sqrt{s}=161$ GeV has allowed the independent determination of $m_W = 80.40^{+0.22}_{-0.21}$ GeV/ c^2 , to be achieved⁷.

4 Extraction of W decay Branching Ratios

The W decay fractions into leptons and hadrons are extracted in a similar way as the cross-sections, by fitting the numbers of events selected in different decay channels. The LEP results are the first direct measurements of all W decays, and are summarized in table 1. The results of the leptonic branching ratios constitute the first test of the $e-\mu-\tau$ lepton universality of charged currents at the m_W scale. The two-by-two comparisons of the three leptonic fractions confirm this universality at the 2-3% level. The W hadronic branching ratio is extracted assuming universal lepton flavour couplings, the result is in good agreement with Standard Model predictions

and can be used to constrain the CKM quark mixing matrix V_{ij} yielding

$$\sum_{i=u,c;j=d,s,b} |V_{ij}|^2 = 2.039 \pm 0.025 \quad \text{and} \quad |V_{cs}| = 0.996 \pm 0.013.$$

These results constitute a good test of the CKM matrix unitarity in the first two families, and the best current constraint on the $|V_{cs}|$ amplitude.

Table 1: Summary of preliminary W branching fractions measurements obtained with the full LEP W-pair data samples. The hadronic branching ratios are obtained under the assumption of lepton universality.

		ALEPH	DELPHI	L3	OPAL	LEP
BR(W $\rightarrow e\nu_e$)	[%]	10.95 \pm 0.31	10.36 \pm 0.34	10.40 \pm 0.30	10.40 \pm 0.35	10.54 \pm 0.17
BR(W $\rightarrow \mu\nu_\mu$)	[%]	11.11 \pm 0.29	10.62 \pm 0.28	9.72 \pm 0.31	10.61 \pm 0.35	10.54 \pm 0.16
BR(W $\rightarrow \tau\nu_\tau$)	[%]	10.57 \pm 0.38	10.99 \pm 0.47	11.78 \pm 0.43	11.18 \pm 0.48	11.09 \pm 0.22
BR(W \rightarrow hadrons)	[%]	67.33 \pm 0.47	68.10 \pm 0.52	68.34 \pm 0.52	67.91 \pm 0.61	67.92 \pm 0.27

5 Conclusions

The measurements of W production and decay rates at LEP has been a nice and exciting work, providing diverse and crucial new results to particle physics on the structure of gauge boson couplings, on the W mass, on lepton universality and on quark mixing.

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